Climatological characteristics of the tropopause parameters derived from GPS/CHAMP and GPS/SAC-C measurements

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Abstract

We have analyzed the tropopause parameters using the data retrieved from the GPS occultation experiment on board the CHAMP and SAC-C satellites. In the present study we have considered 3-4 years of data. Tropopause parameters such as temperature, height, pressure, and potential temperature have been separately studied for the tropical and other regions. Comparison of the temperature profiles (obtained near the equator) by the CHAMP and SAC-C satellites with the radiosonde measurements indicates very good agreement at altitudes below the tropopause. Deviations of 1-2 K are seen above the tropopause level. Analysis of the tropopause parameters separately done for the tropics (20ºS – 20ºN) indicates annual variations. The tropopause temperature and pressure variations are strongly correlated, and they both anti-correlate with the tropopause height. Annual oscillation is evident in the variations of tropopause parameters. The sampled data indicate some interannual variations. We have found that there are some differences between the cold point tropopause (CPT) and lapse rate tropopause (LRT) methods of estimates. The global structure of the tropopause indicates clear differences between the tropics and high latitude regions. Seasonal variation is evident in the parameters; however, they are more prominent in the polar regions. The paper confirms that the CHAMP and SAC-C measurements of the tropopause parameters are complementary as there is very less difference between the two measurements.

1. Introduction

The tropopause is one of the most basic features of the temperature structure of the earth's atmosphere. The exchange of air mass, water, and trace gases between the troposphere and stratosphere takes place across the tropopause. In this context, the tropical tropopause plays an important role [*Holton et al.,* 1995]. Much information on the behavior of the tropical tropopause has been derived from radiosonde data [*Reid and Gage,* 1981, 1985, 1996*; Krishna Murthy et al.,* 1986*; Gage and Reid,* 1987*; Selkirk,* 1993*; Randel et al.,* 2000]. These radiosondes on board meteorological balloon are launched twice a day (0000 GMT and 1200 GMT) from nearly 1,000 weather stations worldwide, and routinely monitor wind and temperature profiles below 25 km. Recently, a number of observational studies have identified decadal-time-scale changes in tropopause height. A review article by *Ramaswamy et al.* [2001] shows the current knowledge on stratospheric trends. *Highwood and Hoskins* [1998] employed European Centre for Medium-Range Weather Forecasts (ECMWF) analysis for 4 years period (1991-1995), along with monthly mean radiosonde data, to study the tropical tropopause. The use of long ECMWF reanalysis data for 1979-1993 to study the pressure, temperature, humidity and wind at the tropopause globally have been conducted by *Hoinka* [1998, 1999]. Recently, *Seidel et al.* [2001] used data from 83 radiosonde stations around the globe during the period of 1961 to 1990 to study the tropopause climatological statistics. Their results indicate an increase in height of about 20 m/decade, a decrease in pressure of about 0.5 hPa/decade, a cooling of about 0.5 K/decade, little change in potential temperature, and a decrease in saturation volume mixing ratio of about 0.3 ppmv/decade. *Randel et al.* [2000] compared tropical tropopause temperature and pressure values using the National Centers for Environmental Prediction (NCEP) reanalysis with radiosonde observations, and found systematic large biases in both temperature and pressure. Using the Lapse Rate Tropopause (LRT) method, they provide reasonable information on seasonal and interannual variations in the tropical tropopause. These observations are nearly dense enough over land, but are not made over sea, except for a few weather balloons launched from ships.

The Global Positioning System Meteorology (GPS/MET) program [*Ware et al.,* 1996; *Rocken et al.,* 1997] established in 1993. The GPS-based Radio Occultation (GPS-RO) technique exploit signals received on board a Low Earth Orbiting (LEO) satellite for atmospheric limb sounding. GPS-RO technique has been very useful in collecting the global high-resolution dataset of temperature, pressure, and refractivity profiles in the atmosphere. Initial investigations of the temperature variations in the tropical tropopause region, based on GPS-RO measurements, were performed by *Nishida et al.* [2000] and *Randel et al.* [2003]. *Tsuda et al.* [2000] have evaluated/determined height variations of gravity waves associated potential energy in the equatorial and mid latitude regions using temperature profiles obtained from the GPS/MET data. First applications of the global and tropical tropopause parameters on the basis of CHAMP RO measurements for the period of May 2001 to November 2003 have been discussed by the *Schmidt et al.* [2004] and validated with ECMWF analysis and radiosonde measurements. The temperature profiles shown by *Hajj et al.* [2004] from CHAMP and SAC-C measurements were accurate to about <0.5 K between 5-20 km with a vertical resolution of ~100 m.

In this paper we use CHAMP and SAC-C observations conducted during the period 2001-2004 to study the tropopause structure. Although there were some publications using the GPS/MET, CHAMP, and SAC-C datasets, those studies gave much attention to the tropical tropopause characteristics [e.g., *Nishida et al.,* 2000;

Hajj et al., 2004; *Schmidt et al.,* 2004]. Here we have used a larger dataset of CHAMP and SAC-C measurements and the comparison is extended to other latitude sectors and gives more on climatological trends. In the next section we give some details of the data analysis. Results of the present analysis begin with the comparison of the satellite and radiosonde derived temperature profiles. Then we show monthly and seasonal variations of tropopause structure in the equatorial region at 20°S - 20°N. We also made an attempt to compare the seasonal behavior of the global tropopause structure using the CHAMP and SAC-C datasets. Finally, the conclusions of the present analysis are summarized in section 4.

2. **Data Analysis**

GPS radio occultations are active limb sounding measurements of the Earth's atmosphere, with the advantages of global coverage, high vertical resolution, self-calibration, and capability to operate under all-weather conditions. By placing a GPS receiver on a low earth orbiter (LEO), the phase delays of GPS carrier signals induced by the intervening medium can be accurately measured as the GPS-LEO satellite link descends through the atmosphere. Given an accurate determination of the positions and velocities for the GPS and LEO satellites and assuming the validity of geometric optics and local spherical symmetry of the atmosphere, the phase delay measurements can be directly inverted to yield the index of refraction profile with vertical resolution that varies from about 0.5 km in the lower troposphere to about 1 km in the lower stratosphere [*Kursinski* et al., 1997; *Hajj et al.*, 2002]. Coupled with the hydrostatic equation, the index of refraction profile can be converted unambiguously into temperature profile above ~5 km, where water vapor contribution is small. This concept of GPS occultation was successfully demonstrated in the GPS/MET (GPS

Meteorology) mission in 1995 [*Ware et al*., 1996]. The more recently launched, polar orbiting, German CHAMP (Challenging Mini-satellite Payload) and Argentine SAC-C (Satelite de Aplicaciones Cientificas-C) satellites each carries a new-generation occultation-enabled GPS receiver, the "Blackjack" supplied by the Jet Propulsion Laboratory (JPL). The two satellite GPS receivers have been collecting occultation data nearly continuously since 2001, with a typical throughput of about 200 soundings per day. The data are routinely processed at JPL, and are publicly available. The details of the CHAMP system and technical features are mentioned by *Reigber et al.* [2000, 2003]. The occultation data analysis system at JPL involves mainly (i) data collection, (ii) orbit determination, (iii) calibration process, (iv) retrieval process and (v) quality control process and these are clearly explained by the *Hajj et al.* [2004]. Both the GPS CHAMP and SAC-C temperature data used for this study are produced by the JPL retrieval software. The data provide global coverage with more than one hundred temperature profiles per day. The retrieval uses Abel inversion under the assumption of hydrostatic equilibrium, spherical symmetry of the atmosphere about the ray tangent point, a refractivity expression and the equation of state [*Hajj et al*., 2002]. Water vapor is negligible except in the lowest 5 km of tropical atmosphere where NCEP analysis is used to provide water vapor profile. The NCEP temperature at 30 km is used as an initial guess in the JPL retrieval.

This study considers a data sample for 44 months that begins from May 2001 to December 2004 for CHAMP and 40 months from July 2001 to December 2004 for SAC-C occultation datasets. An example of the global coverage from the CHAMP and SAC-C occultation for the month of July 2002 is shown in Figure 1(a & b), where the global occultation coverage and distribution of the total number of occultation (4603 for CHAMP and 3235 for SAC-C) are illustrated. From the figure, we can see that occultations in the tropics were lower in density than in the high latitudes. This is due to the high inclination of CHAMP and SAC-C and their viewing geometry relative to GPS [*Hajj et al.,* 2004]. Figure 2(a) and 2(b) shows the histogram of number of occultation for each month of CHAMP (Figure 2a) and SAC-C (Figure 2b) observations. The total number of occultation for the CHAMP is 147,716 for the ~44 months from 14 May 2001 to 31 December 2004 and the occultations for SAC-C are 90,865 during the ~40 months from 6 July 2001 to 31 December 2004.

3. Results

Figure 3(a) and (b) compares the height profiles of the temperature obtained by the CHAMP, SAC-C and radiosonde measurements. The temperature profiles are plotted for the altitude interval 1-30 km. The height resolution of the radiosonde observations varies from 200 m at lower heights to 300 m at upper heights. Radiosonde data are interpolated to 200 m range resolution by applying the spline interpolation technique so as to compare with satellite data of 200 m resolution. In Figure 3(a) we show the CHAMP profile observed at 11:30 on 2 November 2002, at the location with the coordinates 1.82ºN, 102.8ºE. In this figure we also plotted the NCEP and radiosonde profiles at Sepang (2.71ºN, 101.7ºE). The radiosonde data for Sepang are chosen because it is close to the CHAMP observation time and not very far from the CHAMP location. Excellent agreement between the profiles is observed at all heights below the tropopause. However, above the tropopause level some deviation is observed particularly in the radiosonde measurements, which is likely due to smoothing biases. Discrepancies between the CHAMP and radiosonde temperatures are ~1.0-1.5 K at altitudes above 15 km. *Schmidt et al.* [2004] compared the CHAMP temperature data with nearby radiosonde observations. They used the radiosonde launched within a distance of less than 300 km and with a time delay less than 3 hours from the CHAMP measurement and found that temperature bias is less than 0.5 K in the upper troposphere and lower stratosphere height region. Note that the JPL methodology is quite similar to the GFZ (GeoForschungsZentrum) methodology used by *Schmidt et al.* [2004]. However, there could be subtle differences in data calibration (i.e., extraction of excess phase delay), orbital computations, and retrieval parameters. The main retrieval differences are in treatment of the upper boundary conditions for the refractivity and temperature retrievals. A detailed exposition of these differences is beyond the scope of this paper. Comparisons made between GFZ and JPL temperature retrievals based on one month of CHAMP data showed that their mean differences are less than 1 K between 10 to 20 km altitudes [*Ao et al.,* 2003].

Figure 3(b) presents the comparison results for the SAC-C, NCEP, and radiosonde profiles. Here the radiosonde profile is obtained for Singapore (1.36ºN, 103.98ºE) and the SAC-C (7 August 2002) occultation temperature profile refers to 2.01ºN, 101.57ºE, which corresponds to the closest pass to Singapore. Similar to the results in Figure 3(a), the SAC-C, NCEP and radiosonde temperature profiles resemble well at altitudes below the tropopause. The differences observed at altitudes above the tropopause are 1.5-2.0 K. From the comparisons shown in Figure 3(a) and (b), it can be concluded that the satellite and radiosonde measurements represent similar temperature trends in the troposphere and lower stratosphere regions.

Elaborating the comparison results, Table 1 shows the statistical estimate of the bias between the CHAMP – radiosonde and SAC-C – radiosonde measurements obtained for different latitude sectors. The altitudes below the tropopause, and above the tropopause are separately considered and the bias is shown in Table 1(a) and (b), respectively. We use collocation criteria between the CHAMP, SAC-C, and radiosonde data of ±2 hours, ±2 degree in latitude and ±10 degree in longitude. This has been accepted as tolerable for coincidences of ground-based and satellite temperature profiles. The data used include the period from March 2002 to December 2003 and the number of profiles utilized for the comparison is also given. It is evident that the mean bias in the troposphere is less than 0.7 K with root-mean-square (RMS) deviations between 0.9 – 1.6 K for the latitude sectors considered here. Both CHAMP and SAC-C cases show considerable resemblance. The bias is comparatively larger in the stratosphere and it is between 0.9 – 1.5 K. Overall, the statistical estimates confirm the reliability of both measurements. *Randel et al.* [2003] observed rms differences of the order of 2-3 K over 10-30 km (GPS/MET – radiosonde comparison) and claimed that none of the mean biases are statistically significant. The 2-3 K rms difference is approximately the same size as radiosonde temperature variances in the upper troposphere lower stratosphere, so that the results are consistent with the level of natural variability. It is also shown that in the stratosphere there are significant temperature fluctuations probably caused by atmospheric waves which produce periodic differences between the GPS/MET and radiosonde profiles [*Tsuda et al.,* 2000].

Next we would like to describe the tropopause parameters. Two different methods are commonly used to define the tropopause. In the cold point tropopause (CPT) method, tropopause is normally defined as the position where temperature is minimum and this method is more important for describing tropical tropopause features. The thermal or the lapse rate tropopause (LRT) is defined as the lowest level at which the temperature lapse rate is less than 2 K/km and the lapse rate average between this level and the next 2 km does not exceed 2 K/km [*WMO*, 1957]. For the determination of LRT characteristics, we have followed the procedure given by *Hoinka* [1998]. This method is particularly useful for the high latitude regions. In the following we discuss the characteristics of the tropopause parameters derived by the CPT and LRT methods. Figure 4 shows the monthly mean tropopause values of (a) potential temperature, (b) pressure, (c) height, (d) temperature, and (e) number of data points, as derived by the CHAMP and SAC-C measurements in the 20°S-20°N latitude sector. We present the data for the period 2001-2004, and the different parameters shown here are estimated using the CPT method. Examining the figures, it can be seen that a systematic annual oscillation prevails in the parameters presented in Figure 4(a)-4(d). Figure 4(b)-(d) indicates that the tropopause pressure and temperature are in phase and they are out of phase with tropopause height. Every year the maximum tropopause height [Figure 4(c)] is observed in Jan/Feb and the minimum tropopause height is observed in Jul/Aug., which corresponds to the winter and summer seasons in the Northern Hemisphere, respectively. In the data presented here, the maximum height (17.6 km) is observed in January 2004 and the minimum height (16.8 km) is seen in July 2004. Both CHAMP and SAC-C derived data show [Figure 4(a)-(d)] considerable similarity. The tropopause is found to be warmest in Jul-Aug and coldest in Jan-Feb. It is found that the tropopause height is 0.5-0.8 km higher when its temperature drops by 5 degrees. During 2003/2004 the SAC-C data points are comparatively smaller than the CHAMP data points [Figure 4(e)].

Using the CHAMP and SAC-C radio occultation reanalysis data, again we have calculated the same parameters described in Figure 4. Here, the parameters shown in Figure 5(a)-(e) were determined by using the LRT method. Monthly mean values used here were obtained by averaging the daily values of tropopause parameters. The vertical bars indicate standard deviation of the data. Basically the features observed here are very similar to that observed in Figure 4 and it confirms the annual oscillation of tropical tropopause parameters. There is good correlation between the CHAMP and SAC-C parameters. For example, the correlation coefficient between the tropopause temperature measurements by CHAMP and SAC-C is 0.75. The coherency of tropical tropopause height variations at several widely separated geographic locations was explored by *Reid and Gage* [1985] and *Gage and Reid* [1987]. The tropopause features observed in the present analysis are similar to the features observed by *Seidel et al.* [2001]; they used radiosonde data from 83 stations.

It is appropriate to show the mean differences observed between the CPT and LRT methods of estimation of tropopause parameters. Tables 2 and 3 show the mean tropopause temperature and height calculated for the 4 seasons during the period 2001-2004, using the CPT and LRT methods, respectively. Both the CHAMP and SAC-C estimates are separately shown in the Table and these estimates represent the latitude sector 20°S – 20°N. In the case of CHAMP and SAC-C temperatures, the CPT estimates are consistently larger than the LRT estimates. However, the difference is marginal (maximum of about 2.4 K). The maximum difference is observed in summer. The rms deviations are in the range 2-3 K. The mean differences observed in tropopause height are generally less than 150 m. The maximum difference is found again in the summer season and in this case also CPT values are larger. The number of occultations used for the CPT and LRT estimates is different and this can contribute to the mean difference observed between the two methods.

Next we would like to describe the longitudinal-latitudinal structure of the tropopause parameters derived from the CHAMP and SAC-C radio occultation measurements during the northern summer (June, July, and August) of 2004. In Figure 6, two columns [(a) and (b)] of contour plots of different parameters derived by the CHAMP and SAC-C are shown. The tropopause parameters are estimated using the LRT method. First describing the tropopause temperature, within the deep tropics it is generally between -74°C (199 K) and -78°C (195 K), while the temperatures less than -78°C occur in the western and central Pacific. This is in agreement with the observations reported earlier by *Gettelman and de Forster* [2002] and *Schmidt et al.* [2004]. The tropopause temperature pattern observed by the CHAMP [Figure 6(a)(i)] and SAC-C [Figure 6(b)(i)] measurements is generally similar. In northern hemisphere summer, the tropical tropopause temperature has less zonal structure, and the minimum occurs over the Indian region. The overall longitude-latitude patterns are very similar to the LRT estimates given by *Highwood and Hoskins* [1998] based on ECMWF operational analysis, ECMWF reanalysis [*Hoinka,* 1998], and NCEP reanalysis [*Randel et al.*, 2000] using the radiosonde datasets.

The global field of the tropopause height is shown in Figure 6(a)(ii) and 6(b)(ii). The maximum LRT heights during June-August are reaching values greater than 17 km at tropical eastern Pacific region and over the southern part of Africa, Indian Ocean, and middle of South America. The global tropospheric pressure field observed by the CHAMP [Figure 6(a)(iii)] and SAC-C [Figure 6(b)(iii)] indicates low tropical values and high ones in mid-latitudes throughout the year. The extra-tropics of the northern hemisphere are characterized by variations between 30 and 60 hPa, whereas in the southern hemisphere the variations range between 30 and 70 hPa. The tropopause potential temperature in the tropics is found to be larger than the mid-latitude or high latitude regions [Figure 6(a)(iv) and Figure 6(b)(iv)].

The global structures of the tropopause parameters derived by the CHAMP and SAC-C RO measurements for the northern winter (December, 2003, January and

February, 2004) are shown in Figure 7(a) and (b). During 2004 winter the tropics generally shows a colder tropopause, typically by about 4°C, than the summer (Figure 6a, b). The temperature above the southern polar region is close to -52°C (221 K), whereas the temperature above the northern polar region is about 6 K lower. In the northern hemisphere the most prominent variability appeared over the north American and the mid-Pacific regions. Simultaneously we can see a significant maxima of tropopause pressure over north America [Fig. 7(a)(iii)]. *Hoinka* [1998] reported a similar maximum pressure above the same region. *Flohn* [1947] also indicated the maximum pressure at 120°W and another weak maximum at 135°W. Further, both CHAMP and SAC-C tropopause pressure values have shown minima along the equator region.

In the tropics and extra-tropics (30°S–30°N) the tropopause height reaches values of ~17-18 km (105–85 hPa). In the Arctic, tropopause pressure is 270 hPa in summer and 240-250 hPa in winter for both CHAMP and SAC-C measurements. *Hoinka* [1998] mentioned that the tropopause pressure is higher in summer and lower in winter. *Moller* [1938] has pointed out that the annual temperature variations are different in the upper troposphere and lower stratosphere. Potential temperatures shown in Figure 7(a)(iv) and 7(b)(iv) have maximum values in the extra-tropical region. Values greater than 390 K are observed by the CHAMP and SAC-C measurements. Comparing the summer and winter features, it is about 315 K in summer and 310 K in winter above the northern polar region, whereas it is about 320 K in summer and 315 K in winter above the Antarctic. *Hoinka* [1998] estimated the tropopause potential temperature values from ECMWF reanalysis data for 15 years period (1979-1993). The present observation is generally comparing well with the estimates by *Hoinka* [1998].

Concentrating more on the polar regions, Figure 8(a)-(d) shows the monthly variations of tropopause height and temperature above the Arctic and Antarctic regions during the time period from mid 2001 to 2004. The CHAMP and SAC-C estimates shown in the figure are calculated by using the individual radio occultation measurements for the Arctic (66.5°N - 90°N) and Antarctic (66.5°S – 90°S) regions. As seen in Figure 8(a & b), the Arctic tropopause is highest and coldest during the winter months, and the lowest and warmest during the summer. The CHAMP (SAC-C) tropopause height [Figure 8(a)] reaches its maximum of 10.85 km (10.97 km) in December 2002 and the minimum of 8.99 km (8.95 km) in April 2002. In the case of tropopause temperatures [Figure 8(b)], SAC-C and CHAMP values are similar with minimum values (~-61°C) reaching in December 2002 and then increasing to -48.2°C in July 2002. It is interesting to note that the 2004 winter [Figure 8(b)] is warmer by ~3°C than the earlier winter seasons. *Manney et al.* [2004] found a major Arctic winter warming in early January and February, 2004 in the lower and middle stratosphere. This Arctic winter warming is the most remarkable one in the ~50 year record of meteorological analyses.

The Antarctic (66.5°S – 90°S) characteristics of tropopause temperature and height as noted by the CHAMP and SAC-C measurements are shown in Figure 8(c) & (d). As for the tropopause height, a clear annual cycle and systematic year-to-year changes are evident. Note that there is a tendency for warm tropopause temperatures associated with low tropopause heights. The Antarctic winter tropopause heights (peak) are comparatively higher than the corresponding Arctic winter condition.

4. Conclusions

The present paper evaluates the global tropopause parameters using the GPS-CHAMP and SAC-C satellite radio occultation measurements. We have utilized 3-4 years of RO data for the analysis. The advantage of using GPS satellite temperature measurements for tropopause parameters is their extensive geographic and temporal coverage. We have given attention to study the tropical and global behavior of tropopause parameters. Comparison of the tropical temperature profiles derived by the CHAMP/SAC-C and radiosonde measurements showed excellent agreement. The observed temperature bias between CHAMP/SAC-C and independent radiosonde measurements is less than 0.6 K at altitudes below the tropopause and the bias rises to a maximum of ~2 K at altitudes above the tropopause.

We have determined the tropopause parameters such as the potential temperature, pressure, height, and temperature using the CPT and LRT methods. The resulting values show some differences between the two methods. However, in each method there is excellent one to one correspondence between the CHAMP and SAC-C values. The data shown in the present study indicate that in the tropics the CHAMP and SAC-C CPT height reaches its maximum in January 2004 and the minimum in July/August 2004. The CPT altitude is higher than the LRT altitude by about 200 m in January and 400 m in August. Both CHAMP and SAC-C tropopause height values have shown minima along the equator in the Indonesian region. The spatial structure and seasonal trends of the tropical tropopause derived from the GPS CHAMP and SAC-C data agree with previous analyses.

Taking the advantage of the global coverage of the CHAMP and SAC-C data, we have further analyzed the features of the tropopause parameters in other regions with particular attention given to the polar regions. We have observed certain differences between the tropics and other latitude sectors. The Antarctic region is characterized by comparatively higher tropopause than the Arctic ones during similar season. The maximum (summer) tropopause temperature shows similar values between the southern and northern polar regions. However, the minimum (winter) values do show some differences.

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Figure captions

Figure 1. Global coverage of temperature data for July 2002 for (a) CHAMP, and (b) SAC-C.

Figure 2. Histogram of number of occultations for each month of (a) CHAMP from May 2001 – December 2004 and (b) SAC-C from July 2001 – December 2004.

Figure 3. Comparison of GPS temperature profiles with nearby radiosonde temperature profiles (a) for CHAMP and (b) for SAC-C satellite measurements.

Figure 4. Climatological monthly means of CHAMP and SAC-C tropical (20ºS–20ºN) tropopause parameters (a) potential temperature, (b) pressure, (c) height, (d) temperature, and (e) number of data points. The method of cold point tropopause (CPT) is used to estimate these parameters for the period of May 2001 to December 2004 and July 2001 to December 2004 for the CHAMP and SAC-C, respectively.

Figure 5. As in Figure 4 but used the lapse rate tropopause method for the estimation of the parameters.

Figure 6. Time average global structure of tropical tropopause parameters (i) temperature, (ii) height, (iii) pressure, and (iv) potential temperature during northern summer (June to August) in 2004 for (a) CHAMP and (b) SAC-C satellite measurements.

Figure 7. As in Figure 6 but for the northern winter season (Dec-Feb) of 2004.

Figure 8. Time series of monthly mean tropopause temperature and heights at Arctic and Antarctic using CHAMP and SAC-C satellite measurements.

Table 1. Statistical estimate of the bias between the CHAMP-radiosonde and SAC-C-radiosonde comparisons for different latitude sectors and for (a) the altitudes below the tropopause and (b) above the tropopause.

(a)

	Below Tropopause			
	CHAMP		SAC-C	
Latitude	CHAMP - Radiosonde	Profiles	SAC-C - Radiosonde	Profiles
0 – 20 N	0.62 ± 0.98	189	0.66 ± 1.02	168
20 N – 50 N	0.57 ± 1.36	379	0.55 ± 1.56	275
50 N – 80 N	0.58 ± 1.04	312	0.51 ± 1.44	228
0 – 20 S	0.68 ± 0.92	175	0.65 ± 1.03	155
20 S – 50 S	0.61 ± 1.45	328	0.58 ± 1.53	267
50 S – 80 S	0.59 ± 1.15	298	0.51 ± 1.06	198

(b)

	Above Tropopause			
	CHAMP		SAC-C	
Latitude	CHAMP - Radiosonde	Profiles	SAC-C - Radiosonde	Profiles
0 – 20 N	1.42 ± 1.06	189	1.48 ± 0.95	168
20 N – 50 N	0.87 ± 1.53	379	0.91 ± 1.56	275
50 N – 80 N	1.01 ± 1.43	312	1.12 ± 1.33	228
0 – 20 S	1.44 ± 1.16	175	1.52 ± 1.03	155
20 S – 50 S	0.90 ± 1.48	328	0.97 ± 1.58	267
50 S – 80 S	0.89 ± 1.05	298	1.02 ± 1.24	198

Table 2. Seasonal mean tropopause temperature and height calculated by the cold point tropopause method for the 20ºS–20ºN latitude sector during the period 2001-2004.

	CHAMP			SAC-C		
Season	Tropopause temperature (°C)	Tropopause height (km)	No. of occultations	Tropopause temperature (°C)	Tropopause height (km)	No. of occultations
Winter (D,J,F)	-81.52 ± 2.87	17.38 ± 0.33	2853	-81.22 ± 1.19	17.36 ± 0.27	1272
Spring (M,A,M)	-80.19 ± 3.12	17.15 ± 0.37	3428	-80.24 ± 2.79	17.15 ± 0.35	975
Summer (J,J,A)	-77.54 ± 3.03	16.84 ± 0.41	3970	-77.41 ± 3.23	16.84 ± 0.38	2920
Fall (S,O,N)	-78.68 ± 2.54	16.93 ± 0.27	3764	-78.78 ± 2.15	16.92 ± 0.25	3091

Table 3. Same as Table 2 but the values shown are based on lapse rate tropopause method.

	CHAMP			SAC-C		
Season	Tropopause temperature (°C)	Tropopause height (km)	No. of occultations	Tropopause temperature (°C)	Tropopause height (km)	No. of occultations
Winter (D,J,F)	-80.48 ± 3.18	17.40 ± 0.67	2644	-80.11 ± 3.07	17.48 ± 0.77	1208
Spring (M,A,M)	-79.02 ± 2.55	17.28 ± 0.52	3121	-78.97 ± 2.01	17.26 ± 0.48	918
Summer (J,J,A)	-75.18 ± 2.70	16.50 ± 0.87	3698	-75.26 ± 2.88	16.47 ± 0.77	2849
Fall (S,O,N)	-77.80 ± 1.98	16.78 ± 0.72	3432	-76.78 ± 2.12	16.80 ± 0.73	3002

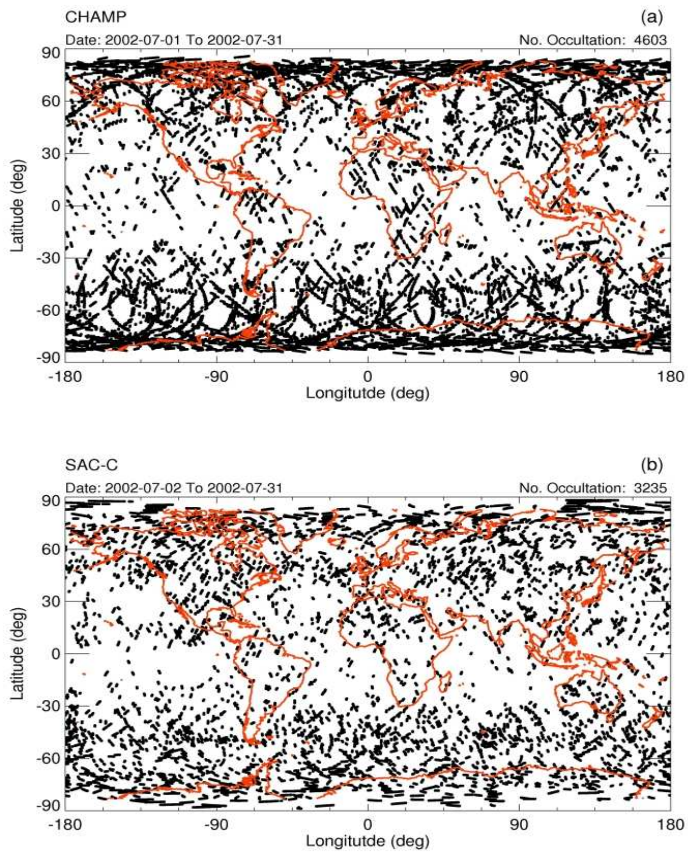


Figure 1. Global coverage of temperature data for July 2002 for (a) CHAMP, and (b) SAC-C.

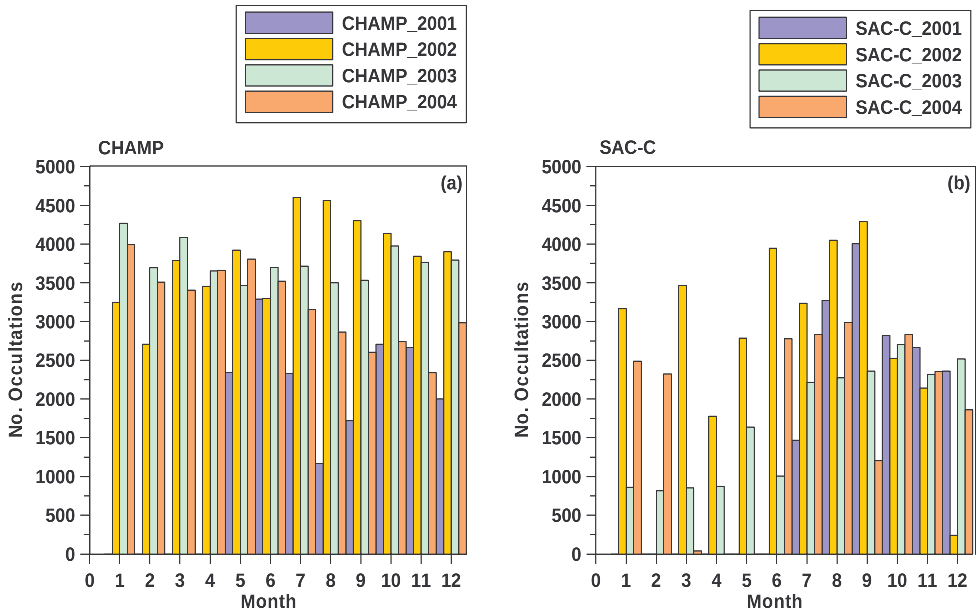


Figure 2. Histogram of number of occultations for each month of (a) CHAMP from May 2001 – December 2004 and (b) SAC-C from July 2001 – December 2004.

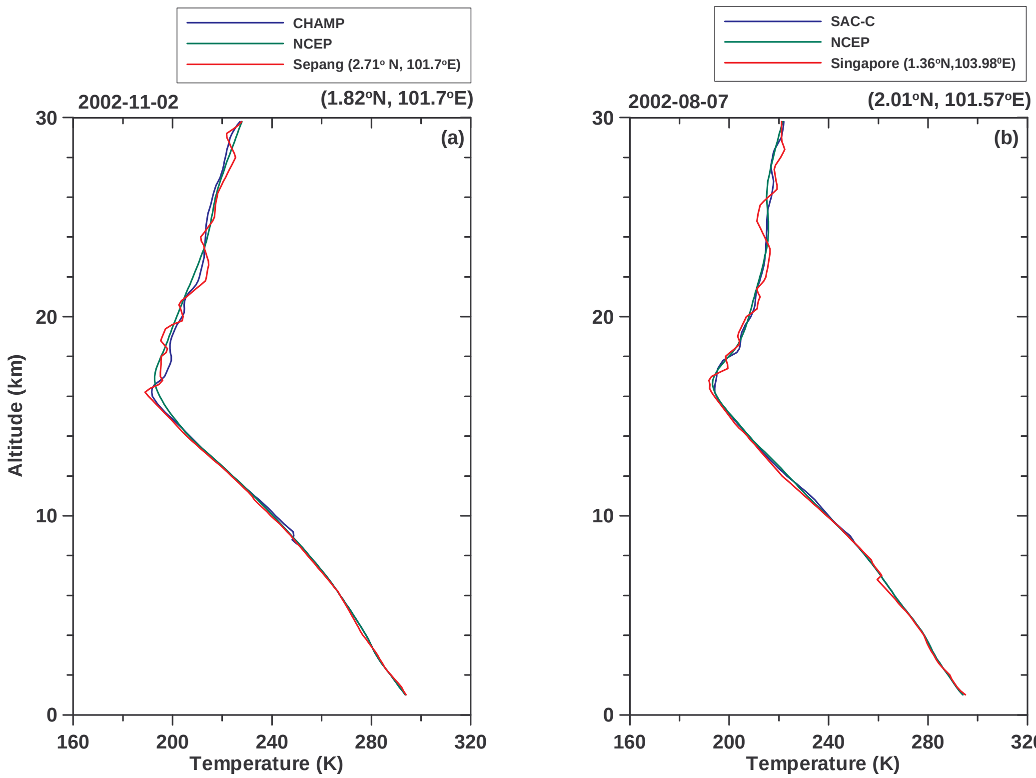
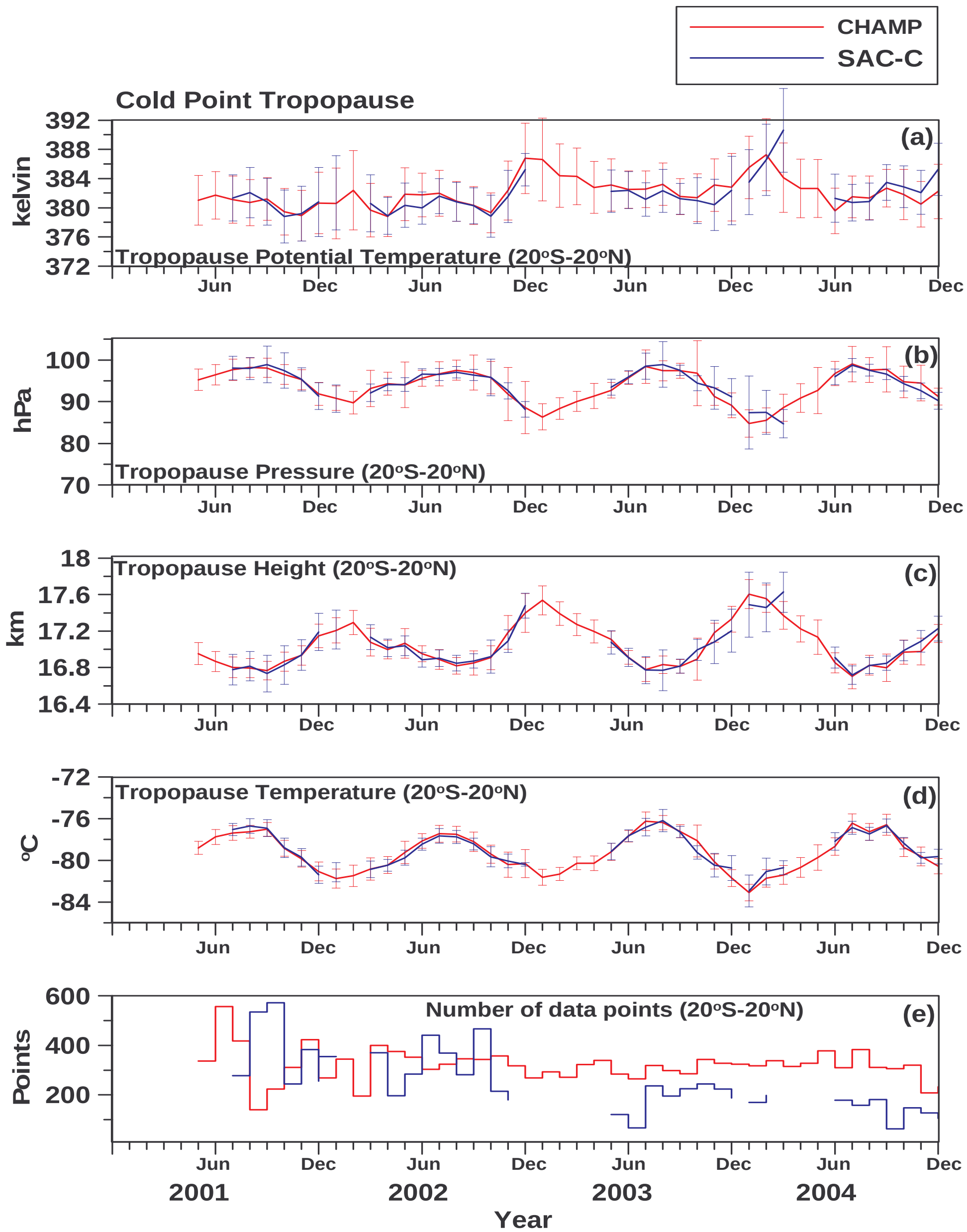


Figure 3. Comparison of GPS temperature profiles with nearby radiosonde temperature profiles (a) for CHAMP and (b) for SAC-C satellite measurements.



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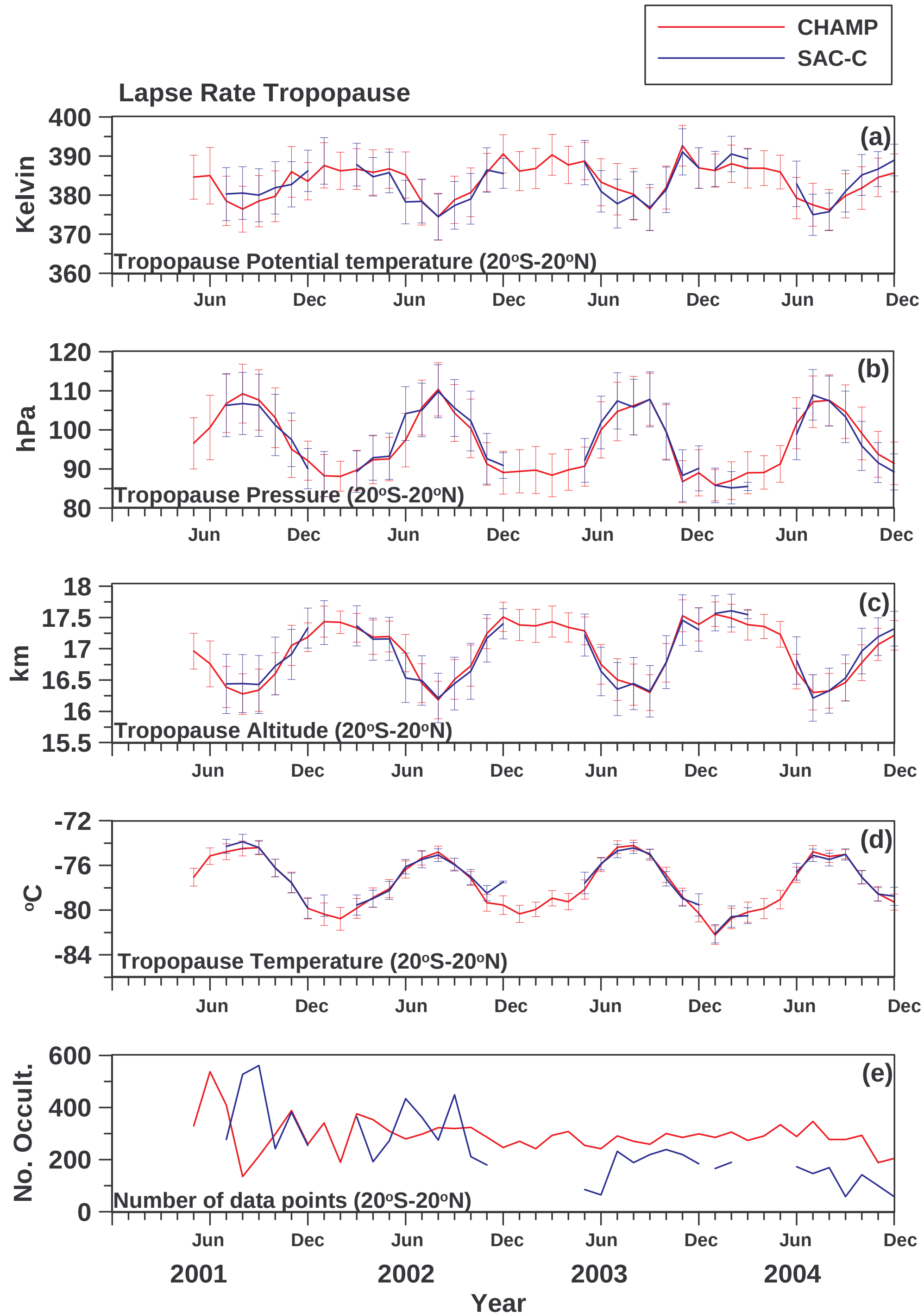


Figure 5. As in Figure 4 but used the lapse rate tropopause method for the estimation of the parameters.

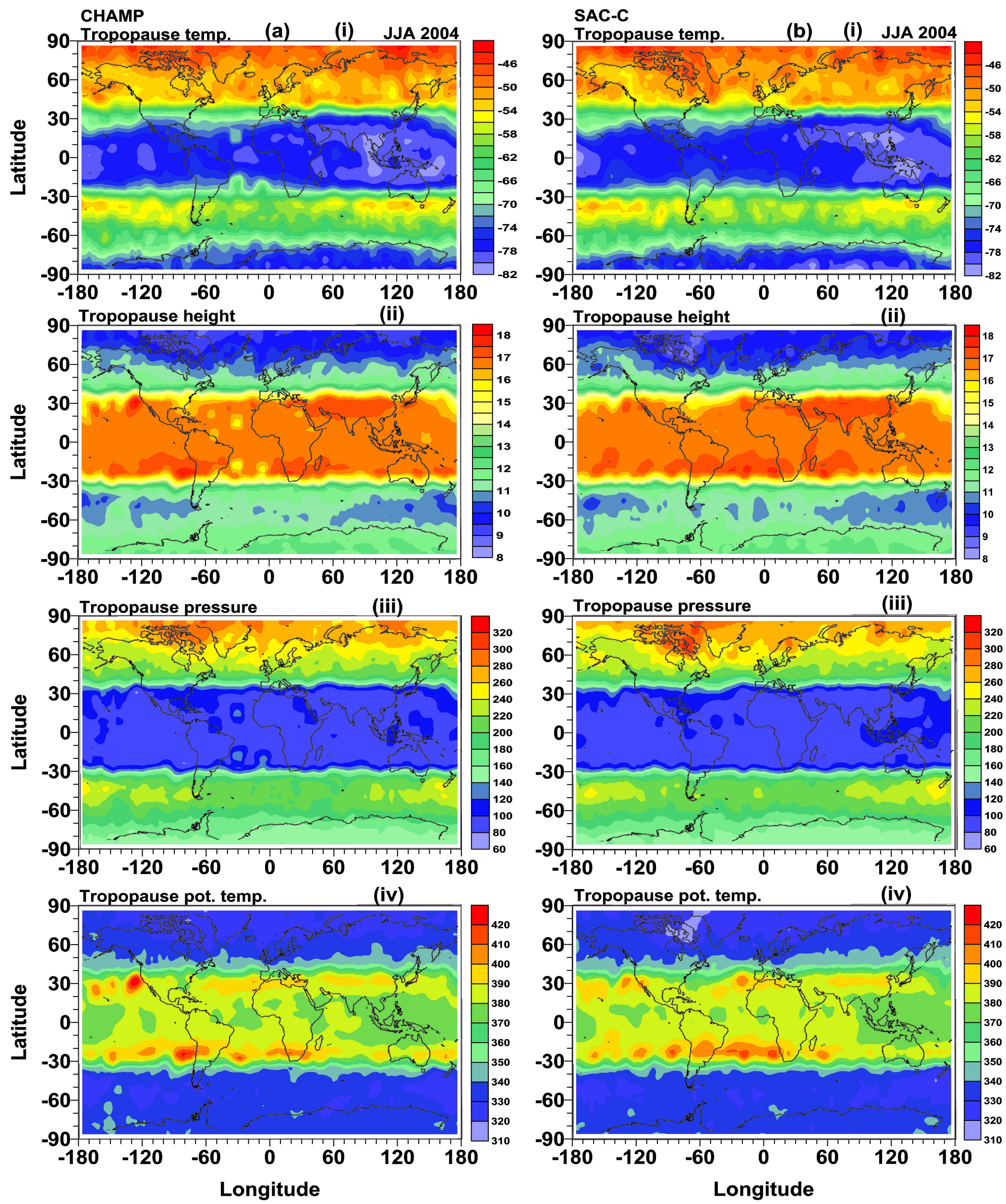
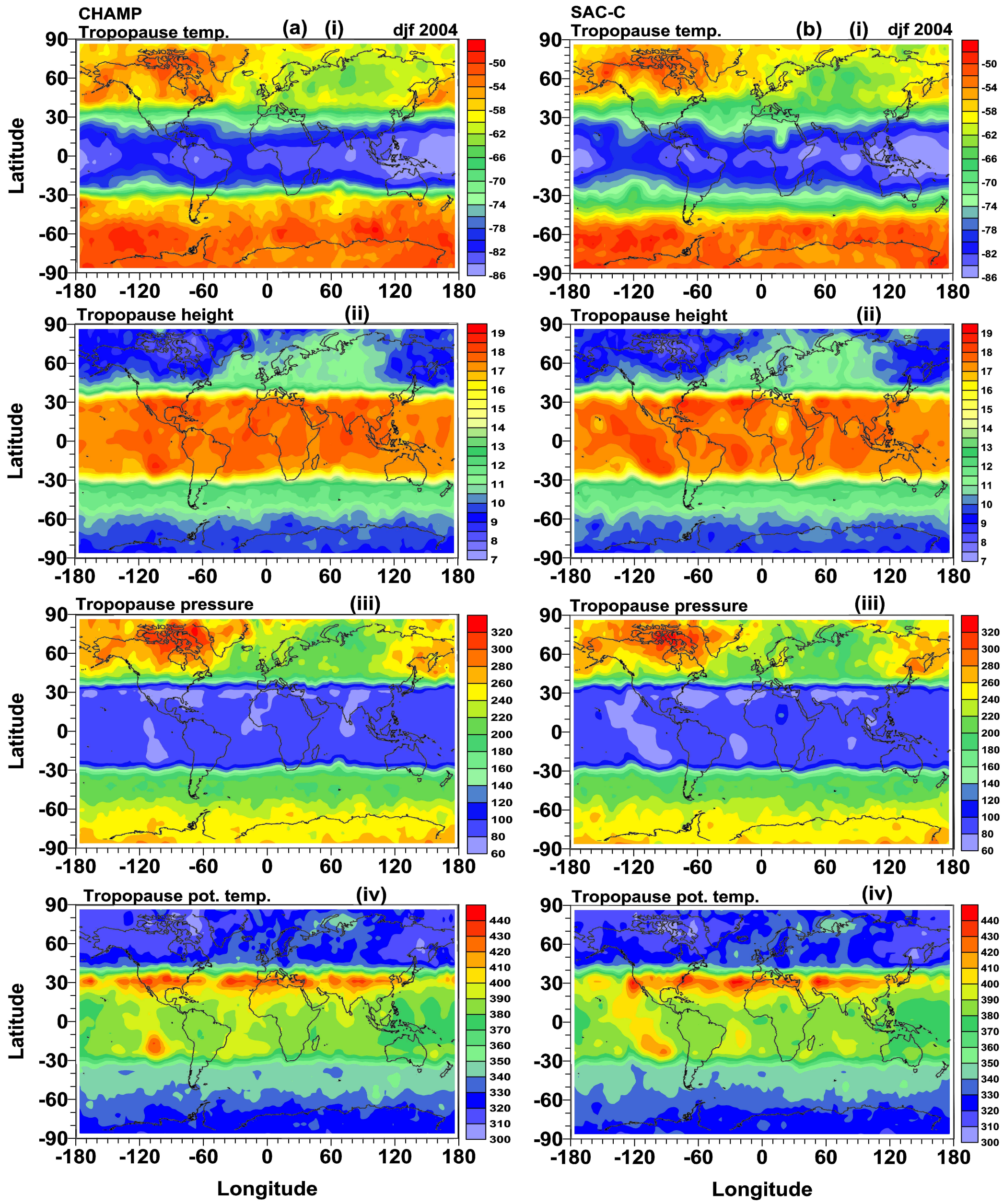


Figure 6. Time average global structure of tropical tropopause parameters (i) temperature, (ii) height, (iii) pressure, and (iv) potential temperature during northern summer (June to August) in 2004 for (a) CHAMP and (b) SAC-C satellite measurements.



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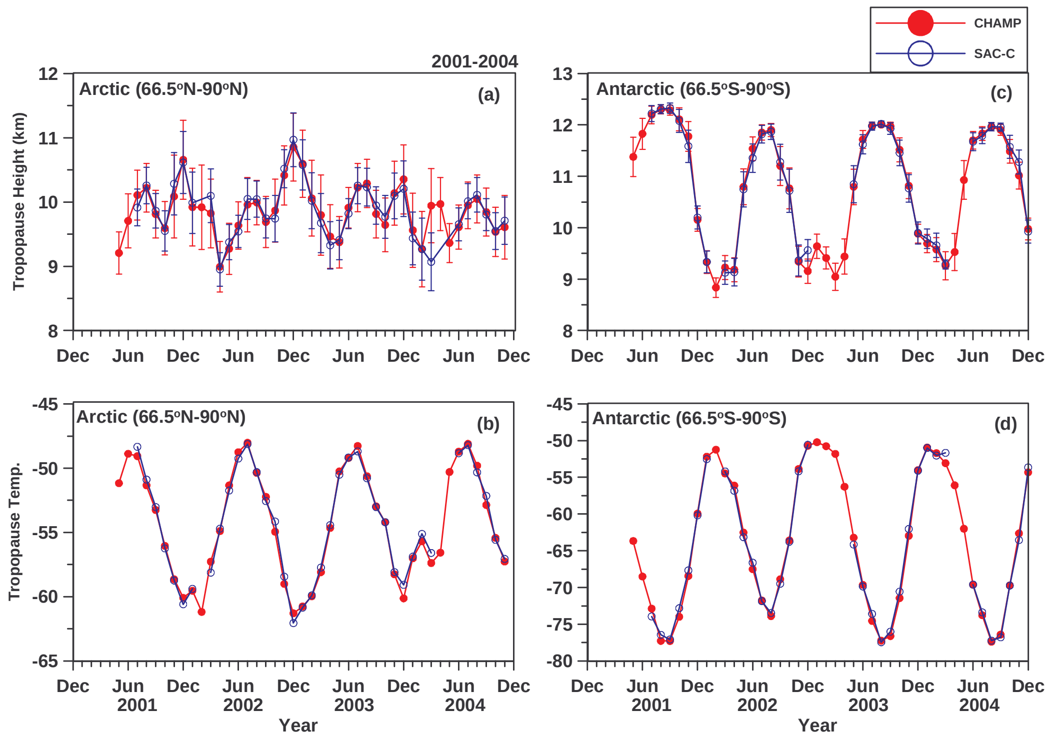

Figure 8. Time series of monthly mean tropopause temperature and heights at Arctic and Antarctic using CHAMP and SAC-C satellite measurements.